Spring Technical Meeting, Central States Section of the Combustion Institute

Fundamental Study of a 7-element Fuel Injector Configuration for Gas Turbine Combustors - A Look at Cold Flow and Burning Measurements

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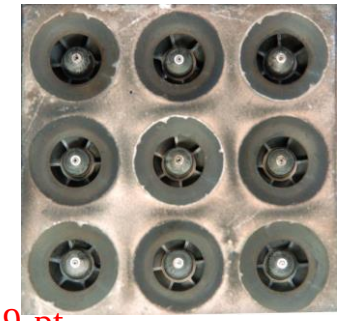
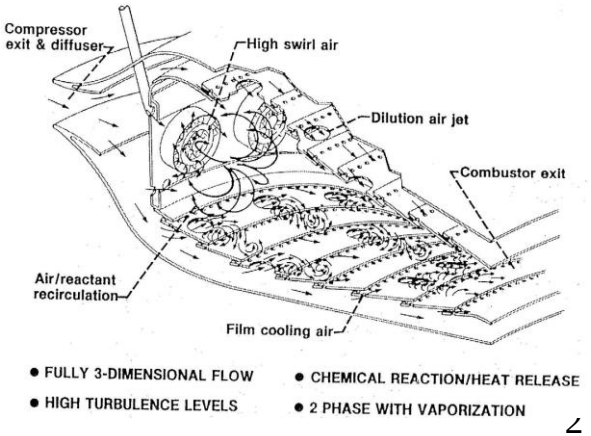
Objectives

- Parametric study to help guide injector design for Low-NOx emissions for aircraft gas turbine engines
- Study fuel-air mixing and combustion using Lean Direct Injection (LDI) as platform. LDI strategy is to inject and mix quickly the fuel and air for uniform distribution to avoid near-stoichiometric burning that would lead to high NOx concentrations
- One goal for the 7-point LDI experiments is to quantify the effect of air swirl angle on recirculation, fuel-air mixing, combustion emissions and flame tube combustor operability

7-pt

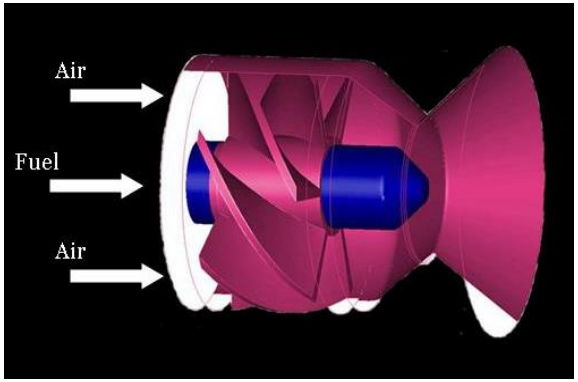


9-pt



LDI Hardware Details

Baseline LDI element

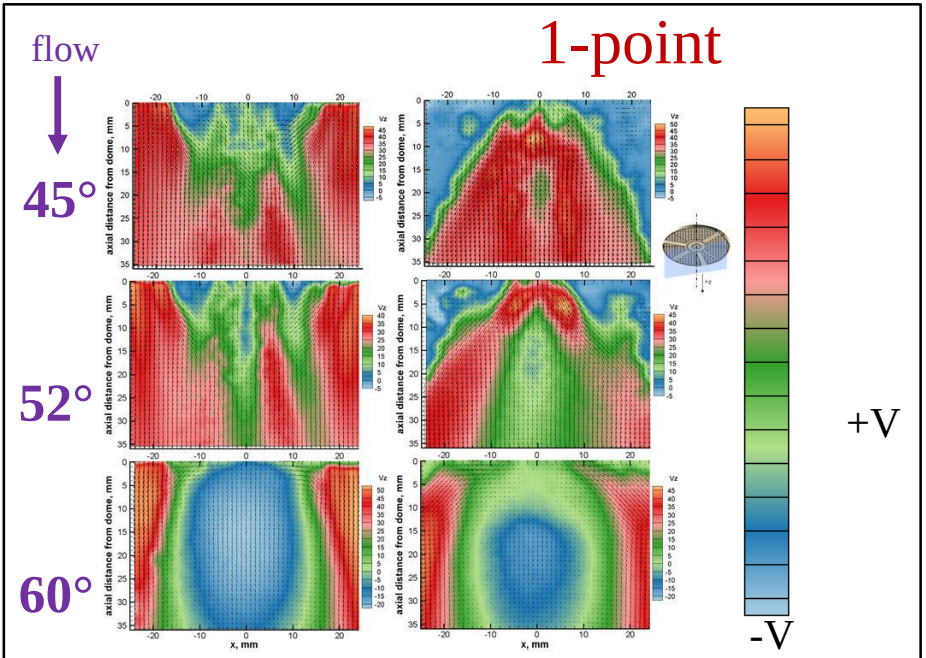


- Six helical angled vanes
- Simplex atomizing nozzle
- Converging-Diverging Venturi

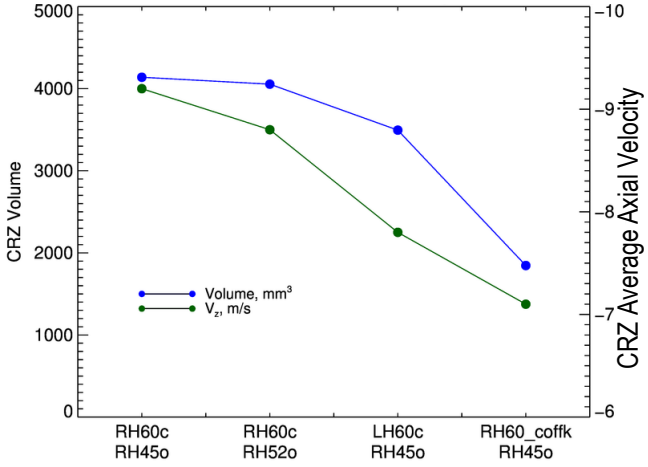
Swirlers: 45°, 52°, 60°
Swirl #s: 0.59, 0.77, 1.02

- 76.2 mm overall diameter
- 23.8 mm between adjacent elements
- Center can be offset upstream to act as a “pilot”

Brief overview of previous LDI tests

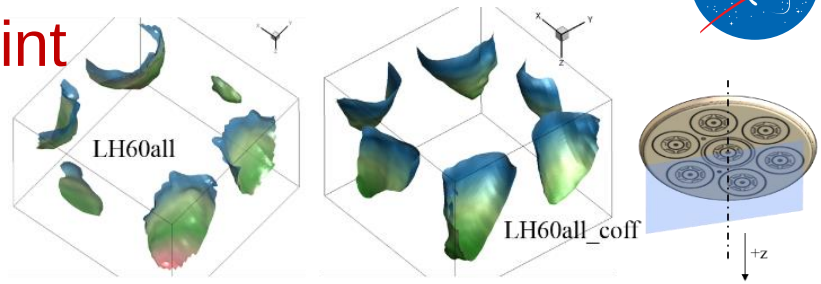


- CRZ only for 60° swirler
- 45° air swirl keeps water confined to a narrow envelope, which expands for the 52.5° swirler, and completely opens up with 60°

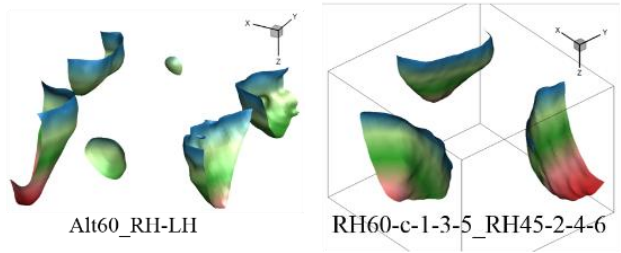


7-point: Center Swirler CRZ: Volume and Average Axial Velocity

7-point



flow

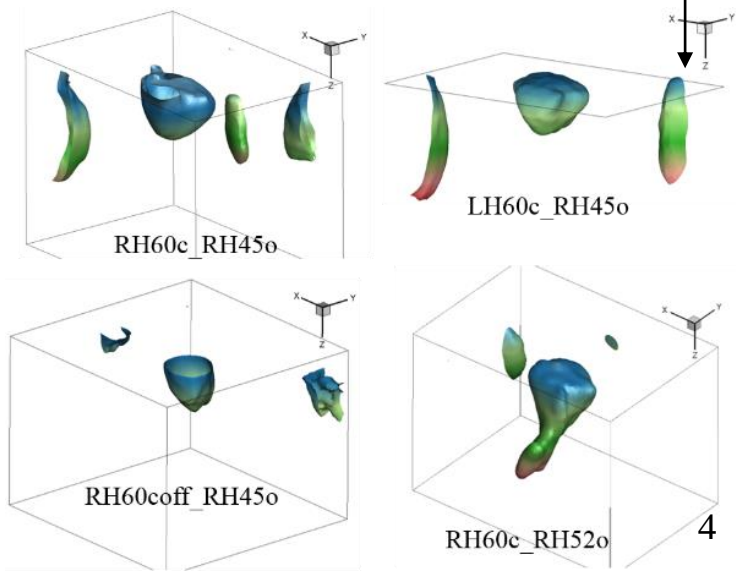


At dome

Re: Center swirler CRZ

Without CRZ

With CRZ



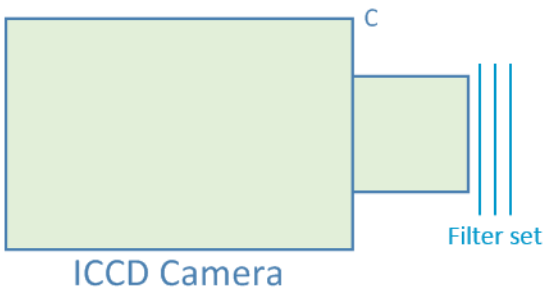
Away from dome

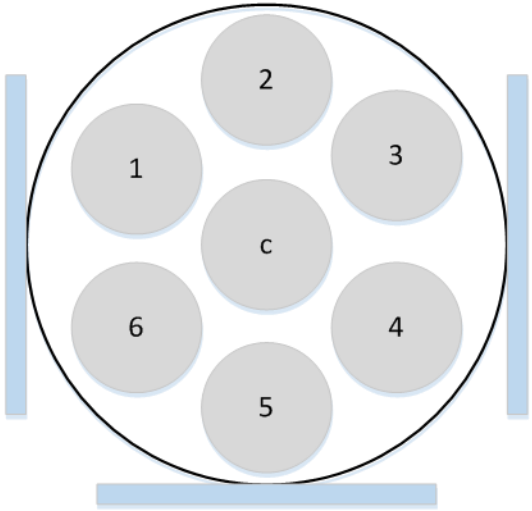
Current Study, counter-swirling configuration

- Center swirler: counterclockwise 60°
- Outer swirlers: clockwise 52°

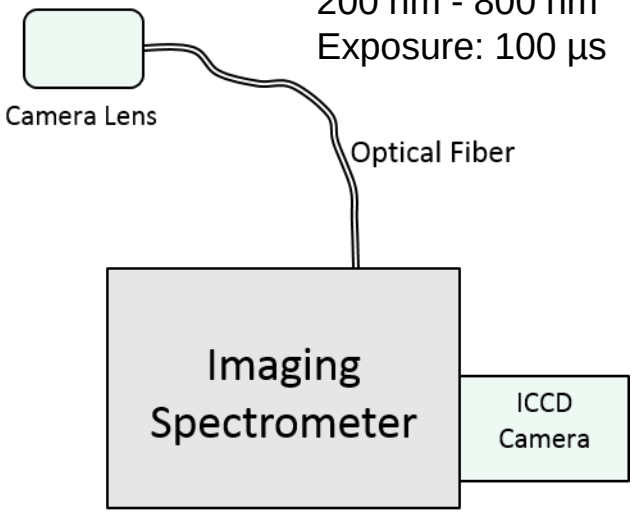
- Non-reacting 2D velocity – determine extent of central recirculation zone
- Chemiluminescence imaging of intermediate combustion species, C_2^*, CH*, OH*
- Flame spectra

Setup used for 7-LDI testing





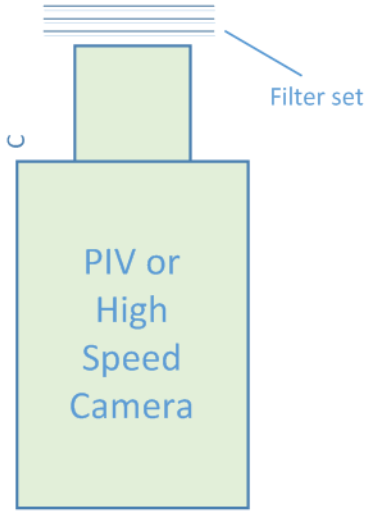
Flame spectra
200 nm - 800 nm
Exposure: 100 µs

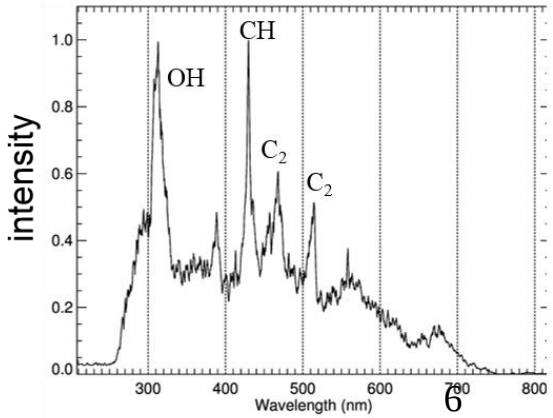


ICCD camera: 1k x 1k pixels
UV intensifier, Super Blue Slow Gate
C_2* chemiluminescence~514-nm
gate: 500-ns

High speed camera: 1k x 1k pixels
40-kHz, 320px x 368 px, exposure: 25-µs
C_2* chemiluminescence~514-nm

PIV camera:
15 image pairs/s





Test Matrix, Data Collection and Processing

T_{inlet} = 800K, P_{inlet} = 5-kPa

Cold flow	**u_{ref}, m/s**		7.6	15.2	22.9	Constant: $\phi \cong 0.35$
Burning	**u_{ref}, m/s**	9.1	10.7	12.2	13.7	Constant: $\phi = 0.45$
	ϕ	0.43	0.45	0.48	0.50	Constant: u_{ref} = 10.7 m/s

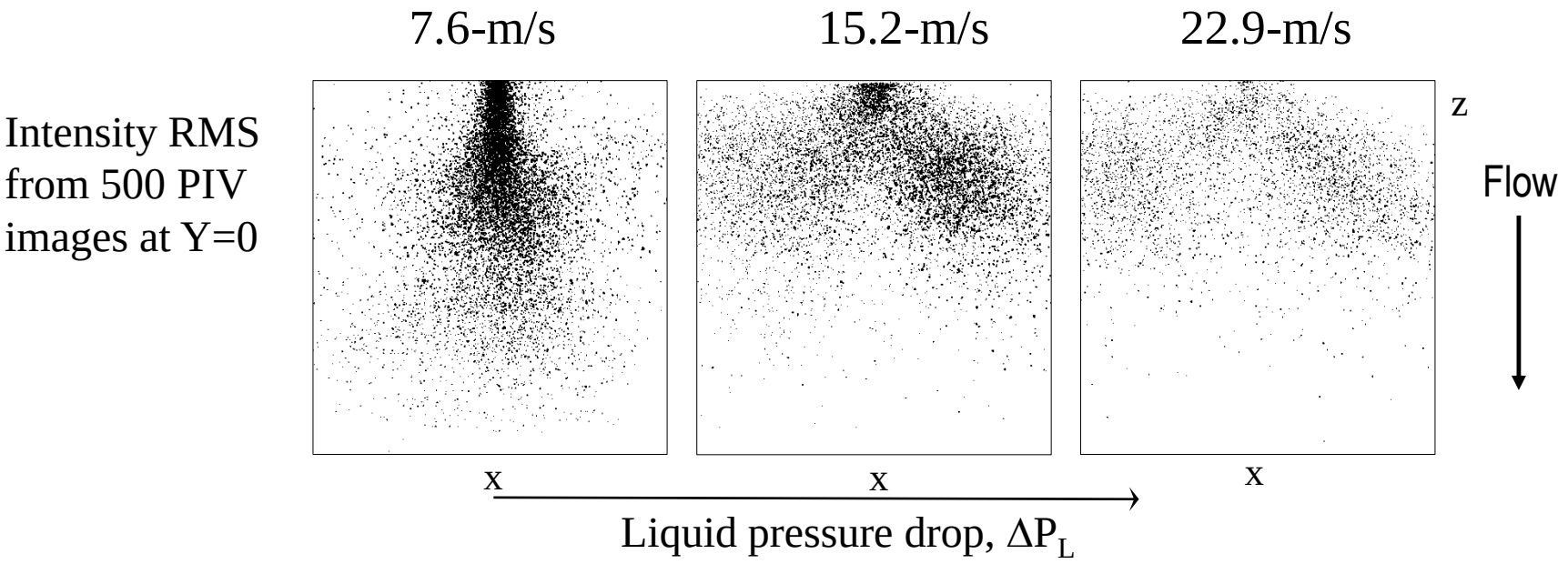
- PIV: 500 image pairs, ~ 15-Hz, 6-ns/laser pulse, traverse y- in 1-mm increments
  - Water seeding through center nozzle
  - Cross-correlation processing for instantaneous, average, and RMS 2D vector fields

- High speed camera: ~ 48000 frames @ 40-kHz frame rate, 25-µs exposures
  - Chemiluminescence imaging—line of sight
  - C2 filter: centered at 510-nm, 8-nm FWHM, 50% transmission
  - Processing: average intensity, RMS intensity

- ICCD camera: 500 frames @ 25-Hz frame rate, 500-ns gate
  - Chemiluminescence imaging—line of sight
  - C2 filter: centered at 511-nm, 11.5-nm FWHM, 50% transmission
  - Processing: average intensity, RMS intensity

On seeding water through nozzle

- Keeps windows clean—air seeding typically does not
- Whether tracks air or water (or both) depends on atomization
- Fuel distribution similar during non-combusting flow



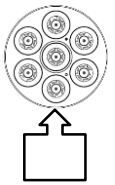
Flow number, FN_{US} = flow rate, pph x $(\Delta P_L)^{-0.5}$

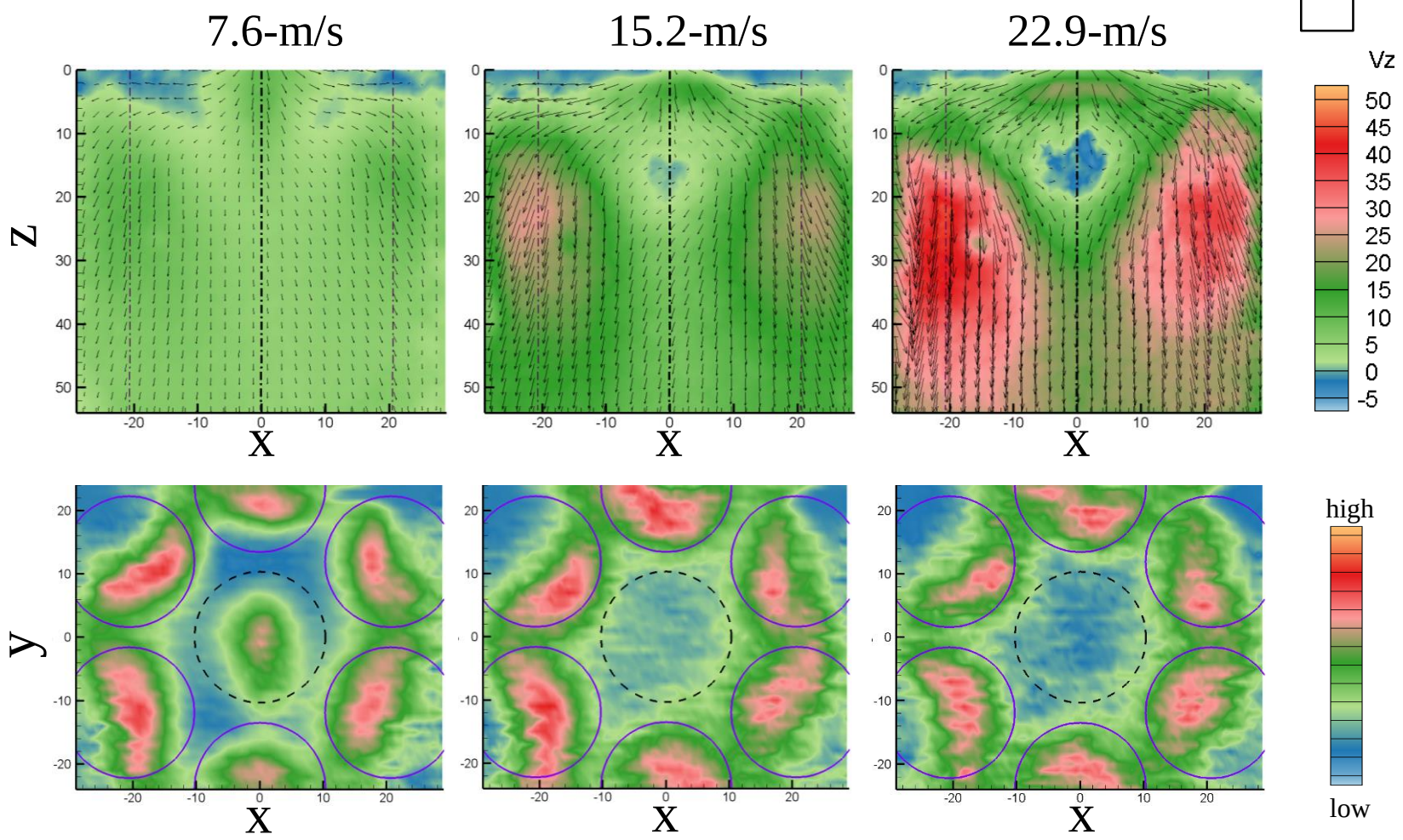
Atomization improves as ΔP_L increases: SMD $\propto (\Delta P_L)^{-0.375}$

Spray penetration S $\propto (\Delta P_L)^{-0.27}$

* Lefebvre, *Gas Turbine Combustion*, 1983.

Cold flow PIV results: mean axial velocity fields



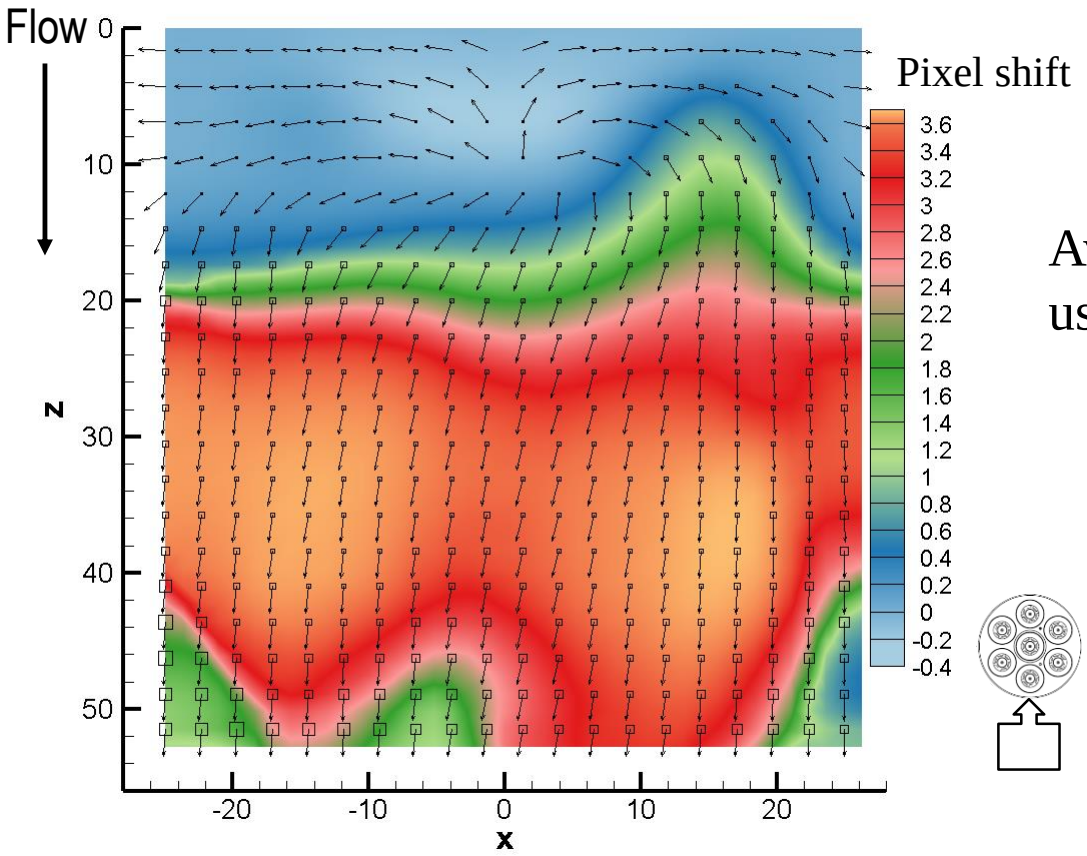


- Increased reference velocity—better tracks air near injector dump plane
- Lowest reference velocity does not indicate recirculation zone in cold flow
- Only highest reference velocity shows distinct CRZ

Combusting results: Tracking C_2* chemiluminescence using high speed camera

Recirculation zone observed, relatively weak (1/9th of max downstream rate).
Only in center of field—likely due to 60° air swirler

Relative magnitude of recirculation on order of cold flow maximum reference velocity

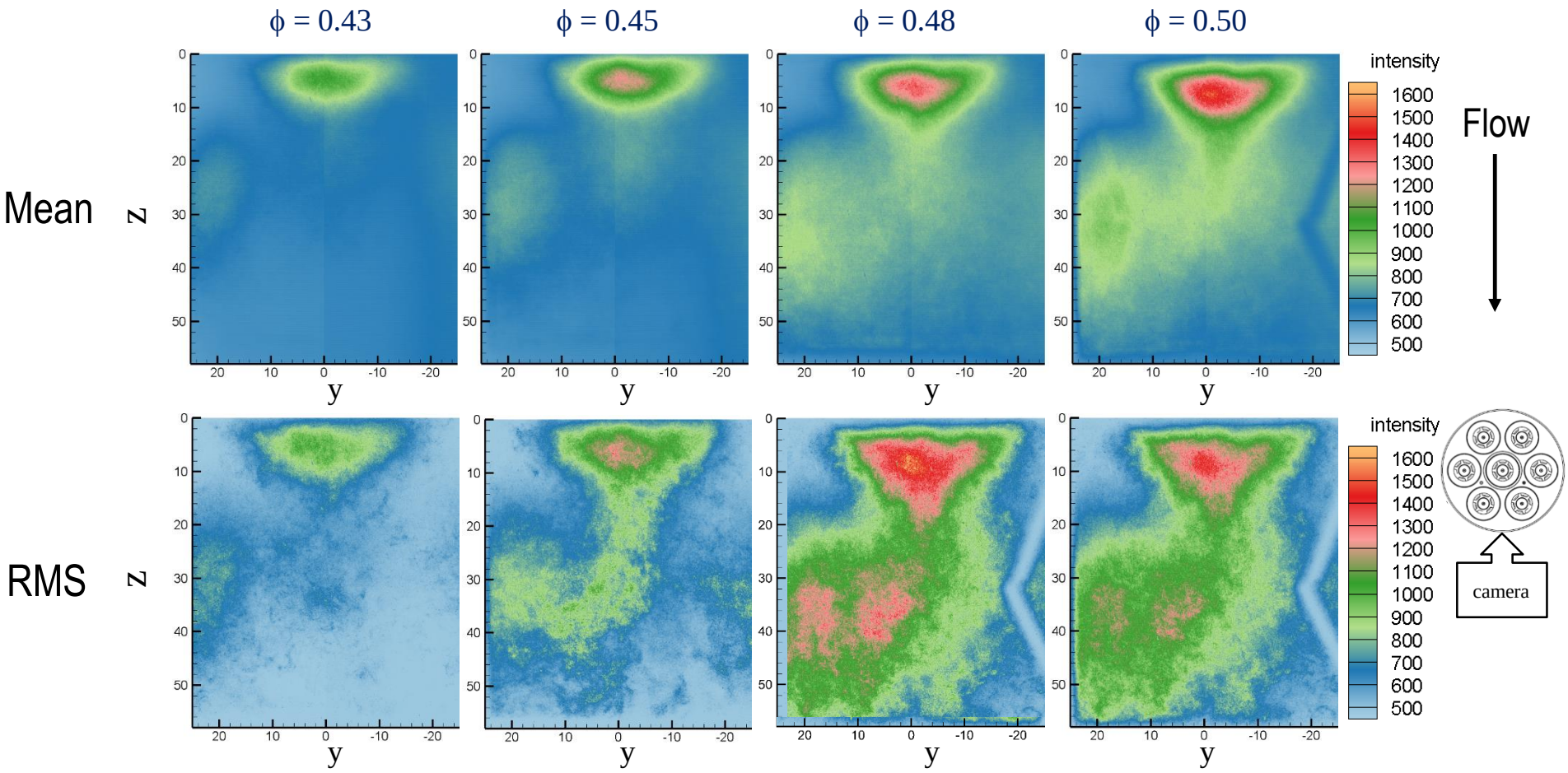


U_{ref} = 13.7-m/s, ϕ = 0.5

Average of 48,000 frames, processed using time-series PIV

Combusting results: Equivalence Ratio Effect, U_{ref} = 10.7-m/s

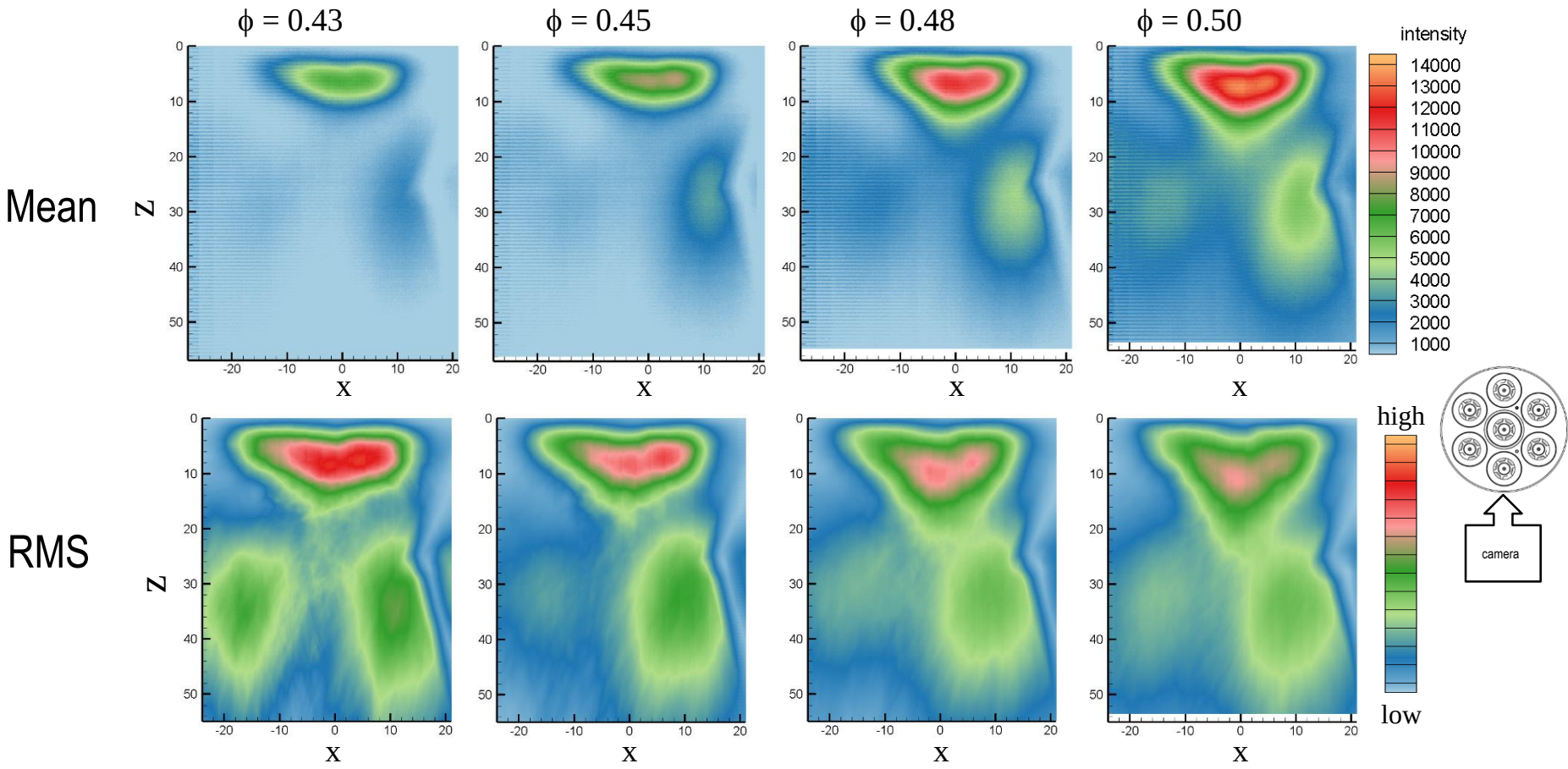
C_2^* chemiluminescence image statistics—ICCD camera



- C_2* intensity increases with equivalence ratio
- highest signal occurs immediately downstream of the dump plane and near center
- Somewhat asymmetric downstream

Combusting results: Equivalence Ratio Effect, U_{ref} = 10.7-m/s

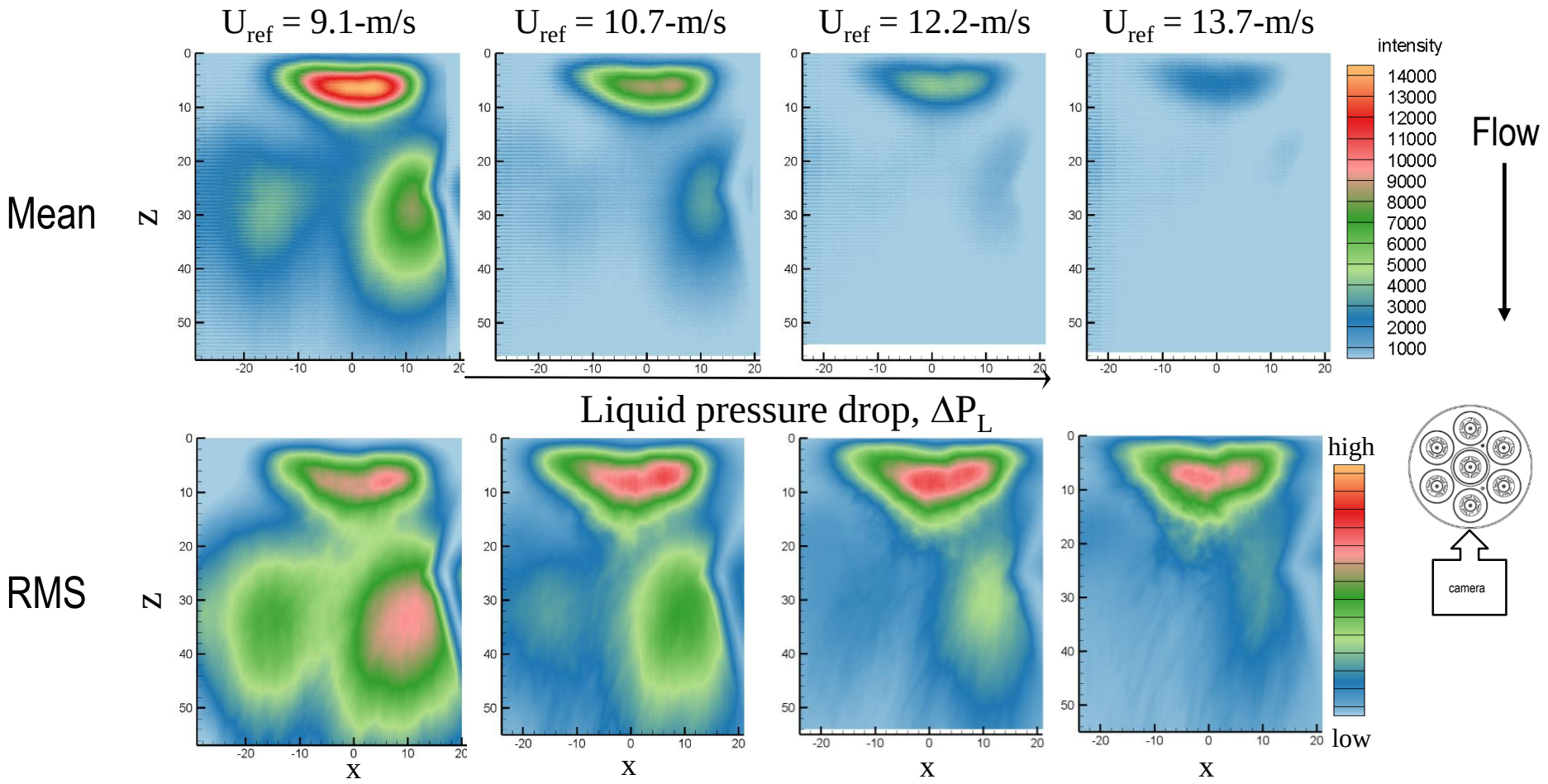
C_2^* chemiluminescence image statistics—High Speed camera



- C_2* intensity increases with equivalence ratio
- highest signal occurs immediately downstream of the dump plane and near center
- Somewhat asymmetric downstream

Combusting results: Reference Velocity Effect, ϕ = 0.45

C_2^* chemiluminescence image statistics—High Speed camera



- overall signal decreases with increasing reference velocity
- better fuel atomization and fuel vaporization
- Increase in air flow → higher turbulence intensity, increased fuel-air mixing

Summary

We presented data from our most recent parametric tests to characterize the flow field of a NASA 7-point LDI injector

- counterclockwise 60° center swirler surrounded by six clockwise 52° swirlers.
- 2D non-combusting velocity fields
  - Highest reference velocity conditions are best indicator of whether a CRZ will develop during combustion.
  - This configuration CRZ amongst smallest compared to previous configurations
- chemiluminescence data in the form of C_2* imaging and flame spectra.
  - for a given air flow rate, the chemiluminescence signal increases with increasing fuel flow rate under fuel-lean conditions.
  - at fixed equivalence ratio, the chemiluminescence signal decreases with increasing air flow rate (reference velocity).
  - This counterswirl configuration generates an asymmetric distribution of C_2* in the downstream region of the outer injectors. The co-swirl configuration did not.

Acknowledgment

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